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Human Efficiency and Comfort in Indoor Climates

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Dr. Herrington highlights the background of human thermal properties which have influenced development of various environmental comfort criteria. The effects upon comfort of various features in the heating and air conditioning situation are discussed, as are human efficiency and safety in relation to thermal environment.

THERE is no scarcity of reference tables, comfort charts, thermal scales, or technical instruments designed to contribute to the optimal regulation of indoor climates. Effective Temperature, Equivalent Temperature, and Operative Temperature are expressions which are familiar to most engineers. All three of these terms refer to extensive and well organized bodies of physical, physiological, and psychological knowledge. The data basic to this knowledge were collected with a single aim, the comfort, health, and efficiency of man at work, rest, or play, in thermally regulated environments. In very recent months two publications have appeared in which, perhaps for the first time, entire volumes are devoted to the technical analysis of man's complex and many-sided relation to his thermal environment. Under these circumstances one may well ask, why give further attention to the thermal comfort factors of the environment? The reasons for this are numerous, and will be given in the summary here:

(1) Despite the existence of reasonably satisfactory guides for the comfort control of indoor spaces, there is very limited general understanding of the human thermal properties which make these standards appropriate.

(2) It is still not common to find a clear understanding of the sensory, circulatory, and postural effects which are the final correlates of thermal comfort even in technical circles that appreciate the quantitative thermal interplay between the human body and the environment.

(3) There is a rapidly growing demand for design and engineering service in the air conditioning field competent to deal with the human as well as the engineering factor in unusual environmental situations. Industrial processing, climatic testing, military installations, as well as some new heating methods demand far more than a knowledge of average satisfactory comfort conditions. The effect of unusual balances in the primary factors of air movement, humidity, and air and radiant temperatures must be understood. In addition, a forehanded estimate of human tolerance for non-optimal thermal environments is often more important than an appreciation of the conditions of optimal comfort.

With the above circumstances in mind, the present article has been organized in three sections which deal successively with (a) the biophysical heat balance of the human body, (b) the comfort significance of special features in the heating and air conditioning situation, (c) human efficiency in relation to optimal thermal environments.

In discussing these topics we must, for the sake of brevity, and because of frequent public presentation, assume first that standard information on comfort conditions such as that available in the American Society of Heating and Ventilating Engineers' handbook is familiar to the reader. In short, the intention is not to review and condense such readily available sources, but to report on less well understood factors beginning with a minimum preface on the basic items of human heat exchange.

The Biophysical Heat Balance of the Human Body

In thermal exchanges between the body and its surroundings, there are four major factors in the picture. The details of this heat interchange as studied by calorimetric methods have been reported by Hardy and DuBois (1)[1], and Winslow, Herrington, and Gagge (2). The human body in a state of equilibrium with its thermal environment produces heat by metabolism. It loses heat by evaporation. It loses or gains heat by conduction, convection, and radiation, depending on the environmental conditions. The whole closed system, when equilibrium exists, may be expressed by a simple formula which combines conduction and convection under the latter term.

$$M \text{ (metabolism)} - E \text{ (evaporation)} \pm C \text{ (convection)} \pm R \text{ (radiation)} = O.$$

[1]Numbers in parentheses refer to bibliography.

States of disequilibrium or temporarily imperfect adjustment often exist and, in some respects, may be of greater assistance in understanding the problem than the condition of full thermal adaptation. In such states the right side of the equation is not zero, but has a positive or negative value, representing actual chilling or heating of body tissues.

A vast amount of literature exists on the details of human heat balance in relation to four physical factors, air and radiant surface temperature, humidity, and air velocity, the measurements of which are commonplace activities for the ventilating engineer.

From the standpoint of comfort the principal problem in this field is simply stated. The human body is a heat generator with a resting rate of approximately 100 watts. Through work this rate may be increased by a factor of 4 or 5 for periods of several hours. All of this heat is lost from the surface of the human body. This exchange follows the engineering laws common to all heat exchangers; and coefficients of heat exchange have been experimentally determined for factors of convection to air, radiation exchange with surrounding surfaces, and evaporation. Comfort enters the problem as a physiological and psychological factor in this manner. The human body prefers a condition in which heat loss is primarily by radiation and convection from a skin surface averaging near 91F to 92F, with a range of approximately 15 degrees between extreme skin values. The lower extreme is found at approximately 80F on the skin of the toes, and the higher value of approximately 95F over the chest area. For a sensation of comfort both the average value and the topographical distribution of skin temperature is important.

At rest and unclothed in an environment with wall and air at 85F, an air movement of 15 fpm, and relative humidity between 25 and 35%, the average individual feels comfortable. The addition of normal male clothing maintains the heat balance and skin temperatures of comfort provided the air and wall temperatures are dropped to approximately 70F. It is seen through this illustration that the heat loss occurs over gradients of approximately 7 to 22 degrees for the respective clothed and unclothed conditions.

The moment we deviate from the above equal conditions of air-wall temperatures, relative humidity, and standard air movement of 15 fpm, the typical temperature difference between skin and environment required to dissipate body heat is changed. In engineering terms this is merely a change in the surface coefficients of heat transfer. However, in comfort conditioning the problem reduces to this statement. The comfort temperature in terms of air temperature varies according to the "mixing" of various levels of air movement, humidity, and radiant wall effect produced by different styles of heating and cooling, and physical properties of the structure, such as degree of insulation.

The problem will not be pursued further than the statement that the current ASHVE Comfort Charts afford excellent guides for the combination of the factors of humidity, air temperature and air movement above 80F. Although apparently overcorrected for humidity below 80F, the error is not serious for moderate ranges of humidity. In addition, we have the Corrected Effective Temperature* developed by the British to incorporate the radiation factor; and Operative Temperature** which is a calorimetric scale particularly useful in special problems requiring consideration of clothing insulation effects.

The practicing engineer engaged in other than routine heating problems can make excellent use of the charts prepared for the Corrected Effective Temperature. As a correlate to their use, wider employment of the black globe thermometer by the profession in determining the net effects of radiation and air temperature would be found highly rewarding.

Human Temperature Regulation

The details of human heat transfer are readily available in sources mentioned and their further description is less in point than an emphasis on the physiological background of this adjustment. In the preceding section it has been shown that rest and work are systematically associated with heat production. The energy for this process is derived from food combustion within the body. Hence, it is possible to consider that human occupancy of confined spaces is analogous to occupancy of the space by multiple engines consuming fuel and producing heat and motion. A characteristic difference between the mechanical and the biological process, however, lies in the low temperature at which human combustion proceeds (near 99F) and the elaborate and sensitive mechanism within the human body which holds its internal operating temperature near

*Thomas Bedford. Basic Principles of Ventilation and Heating. H. K. Lewis, 1948. London. (p. 57)

**C.-E. A. Winslow and L. P. Herrington. Temperature and Human Life. Princeton Press, 1949.

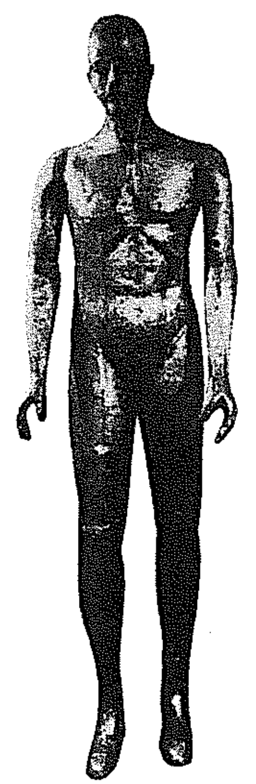

Fig. 1. Electrically heated copper manikin of 19.4 sq ft body area whose heat production may be regulated to correspond to either resting or exercising heat production. Devices of this type are frequently used to estimate the protective value of various clothing assemblages. Representative skin, clothing, and environmental temperatures as observed in seated subjects normally clothed and comfortable with air velocity at 15 to 25 fpm are as follows:

Air and wall	71.6F
Head	92.1F
Arms	91.0F
Trunk	94.1F
Legs	88.9F
Skin average	91.0F
Clothing average	86.9F

to this fixed point, despite large variations in heat production, and wide swings in external temperature.

The reality of this thermal regulation and its efficiency may be illustrated by reference to Fig. 1 and Table 1. Fig. 1 shows a copper replica of the human body. When filled with water and supplied with internal heat equivalent to 0.75 met (1 met = 50 KgCal) per (sq M) (hr) = 18.43 Btu per (sq ft) (hr), the gradient of temperature from the internal water mass through the skin to the outside air in a room at 86F is given in Table 1. By regulation of the fluid circulation rate the gradients of heat loss established may be made quite similar to those found in a resting human subject at the comfortable and thermally neutral condition of 86F. When the temperature of the environment is raised or lowered by 9 degrees, every step in the temperature gradient of the heated manikin reflects in an exact manner the temperature change in the environment. If the human body responded to a change of ± 9 degrees in the environment in the same manner, the individual would be prostrated with heat at 95F, and rigid with cold, perhaps unconscious, at the 77F condition. However, as one may see in Table 1, this is not at all the case. The human data of this table indicate that the deep internal temperature is quite constant over this 18-degree range of environmental temperature. If we add to this primary thermoregulatory ability of the nude body the additional range conferred by voluntary choice of clothing and regulation of heat production through activity, the range of external temperature over which body temperature may be maintained near 99F for limited periods extends at least from —40F to + 135F. There is, however, a substantial physiological cost attached to such survival adjustments, and maximum human efficiency is preserved only in a narrow range from approximately 60F to 80F for the normally clothed subject.

TABLE 1—THERMAL BEHAVIOR OF HEATED MANIKIN AND HUMAN SUBJECTS AT VARIOUS AIR TEMPERATURES

Air Temp, T_a	Unclothed Heated Manikin				Unclothed Human Subjects			
	Skin Temp, T_s	Internal Body Temp, T_b	Gradients		Skin Temp, T_s	Internal Body Temp, T_b	Gradients	
			$T_s—T_a$	$T_b—T_s$			$T_s—T_a$	$T_b—T_s$
95.0	102.2	107.6	7.2	5.4	95.0	98.6	0	3.6
86.0	93.2	98.6	7.2	5.4	93.2	98.6	7.2	5.4
77.0	84.2	89.6	7.2	5.4	84.2	98.6	7.2	14.4

The experienced engineer on examining the gradients of Table 1 will see immediately that there are two classes of effects operating to keep the deep body temperature constant. He will ask: Since a constant quantity of heat is passing from the region at 99F to the skin, why does the thermal head vary from 14.4 degrees at a temperature of 77F to 3.6 degrees at 95F? This mechanism for altering the internal gradient must be an important part of human heat regulation.

This supposition is correct and the physiologist can supply a sufficient answer. The thermal resistance between the deep body region and the skin can be varied. As in a heat exchanger, the transfer of heat from a circulating medium (blood) to the receiving surface (skin) is a function of the velocity of circulation in the system and the thermal resistance of the heat exchanger wall. By dilation of blood vessels in the skin, the skin thermal resistance may be greatly decreased. Through increased rapidity of circulation in the system generally, and particularly in the dilated skin area, thermal head at constant heat production may be varied by 9 to 10 degrees. The physiological cost of this adjustment is borne primarily by the heart. The details of such adjustments in circulation index are described by Hardy and DuBois (1), and by Winslow, Herrington, and Gagge (2).

The engineer will also note that the conditions at the surface of the body as reported in Table 1 are also different from the manikin's response. He will then ask: How is it possible for the standard heat production delivered from skin to air over a 7.2-degree gradient at a room temperature of 77F or 86F to be passed to the air over a 0-degree gradient at a room temperature of 95F?

This question is largely rhetorical since the process of evaporation or sweating is generally familiar to all. The physiologist adds that when the body is subjected to a larger stress than can be met by its internal thermal head reduction mechanism, it stabilizes the skin surface at a value 2 to 4 degrees below internal body temperature by secretion and evaporation of sweat from its external surface. Under these circumstances air temperatures may reach and exceed skin temperature and body temperature.

Neural Integration of Temperature Regulation

We have observed that the body produces heat consistent with different grades of work and eliminates this variable heat input to a variety of thermal environments from a rather constant internal body temperature near 99F. In a very elementary comparison of the thermal response of a heated manikin with that of a human subject, we have isolated the gross physical features of this adjustment. It is important to know how these adjustment resources are controlled and integrated.

The primary element in human temperature regulation is a group of cells located by Ranson (3) in the hypothalamic area of the brain. This temperature regulating center is directly sensitive to temperature. Due to its location and blood supply, it is constantly perfused by blood whose temperature is a representative sample of the thermal state of the important vital tissues and organs of the body. This center operates as a thermostat set normally at 99F for resting levels of activity, but capable of resetting itself for higher levels as total heat production increases. Thus under conditions of strenuous exercise, Nielsen (4) has found that 102.5F is the approximate control point. In contrast with the usual mechanical thermostats, this biological temperature regulator initiates positive adjustments for excesses as well as deficien-

TABLE 2 — THERMAL CHARACTERISTICS WITHIN THE APPROXIMATE THERMAL RANGE OF HUMAN SURVIVAL

Item	Representative Rectal Temp in Lower Range of Survival, 77F	Average 24-hour Rectal Temp, 98.6F*	Representative Rectal Temp in Upper Range of Survival, 109.5F
Calculated average body temp, Burton formula (.65 rectal temp + .35 skin temp)	64.4	96.1	107.6
Total heat content above 32F (154-lb body), Btu	5047	8206	9682
Difference from heat content at 98.6F rectal temp (body av. = 96.1F)	—3159	0	+ 1476
Ratio of above difference to basal heat production at 98.6F	11.4	1	5.3

*Day values usually exceed 98.6F, but the 24-hour average is very near 98.6F.

cies of temperature, and hence, in a gross sense, resembles the dual control of an air conditioning system with both heater and cooler units under its control. Not only are the adjustments which this center may initiate to temperature stress influenced by the actual temperature of the cells which comprise the center, but, through its correlative function, it is also influenced by temperature events affecting the numerous warm and cold sensory receptors of the skin surface according to Bazett (5). Through such interconnections the center is sensitive both to the slow trend of the temperature of the internal body mass and to sudden changes which may occur at the body surface. This gives the regulation what would be mechanically regarded as an anticipatory function. Hardy and Oppel (6) have shown that the heat receptors in the skin are sensitive to changes as small as .0036 degree per second and the cold receptors to .0072 degree. There is no direct evidence as to the sensitivity of the heat regulator in the hypothalamus in man.

The adjustments which the center has under control are of two general classes. The first includes the moment-to-moment emergency adjustments which comprise conspicuous features of temperature control. These are dilation or constriction of peripheral blood vessels, alteration of peripheral blood flow, stimulation of sweat secretion, and stimulation of shivering. These actions are not under voluntary control. Actions that require a voluntary element, but are basically regulative, are impulses to alter posture, to increase or decrease food intake, and to alter levels of physical activity or clothing.

In addition to these immediate reactions, the center is involved through complex nervous interconnections with longer-term acclimatization responses. In this category may fall adjustments in blood volume, in blood chemistry, and in endocrine activity. In animals there are changes in thickness of coat in response to temperature, and probably in both animals and man, fat deposition is influenced by these longer-term effects.

When these various complicated adjustments are considered from the standpoint of comfort, the primary observation is that the preferred thermal situation is that in which occasional variety in thermal sensation is sparingly mixed with average environmental heat demands which provoke only minimal degrees of physiological adjustment.

The conditions of comfort have as a correlate the extremes of discomfort or stress which the human body is able to endure. As a matter of interest, Table 2 has been included, which gives the thermal range of human survival.

While these data do not immediately concern the engineer, they give an excellent idea of the narrow range within which our heat regulatory system operates in contrast to the lethal limits of human temperature experience.

Comfort Significance of Air Movement

There is a substantial difference between the average air movement in a room with wide area floor or ceiling panel heating and a similar space heated or conditioned by an air circulation system. Under usual circumstances, the panel heated room will have a higher average surface temperature than the convection heated room. As a result, attention is frequently drawn to the fact that the comfort point (in terms of air temperature) is lower in radiant panel heated spaces. Such a difference does exist and, as is well known, is more pronounced, the heavier the heating load. Less frequent attention is given to the fact of air movement as a factor in altering the air temperature at which comfort is experienced. Panel heated spaces frequently have air movements somewhat less than 15 fpm, and it is not unusual to find convection systems which are near 30 fpm, or higher in local areas.

In Table 3 a calculation has been made of the effect of variation in air movement on the air temperature required to produce a standard heat loss at various air velocities. The question asked here is: What increase in air temperature is required to balance the cooling effect of increased air movement?

The question is readily answered provided one is willing to make one assumption. This assumption is that the clothing behaves as a close knit *relatively* impervious material. This assumption probably does not introduce any serious error below a velocity of 3 to 6 miles per hour.

From one of the studies at the Pierce Foundation, I have taken a heat partition for a clothed man at rest with air and walls at 16C (60.8F) and air movement 4.6 cm per sec (9.05 fpm). It was found that loss by radiation was 3.32 KgCal per (hr) (sq meter) (C) or .68 Btu per (hr) (sq ft) (F difference between clothing and wall temperatures). The corresponding value for convection loss *at this air movement* is 2.15 KgCal per (hr) (sq meter) (C) or .44 Btu per (hr) (sq ft) (F).

The particular data cited here were selected because of the unusually low air movement and other experimental features which contributed to reliability in the values for radiation and convection loss. Although the subject felt quite cool at the temperature of 60.8F, he was in thermal equilibrium. This fact is important because it means that we can use these data to determine the degree equivalents of increased air movement and then add these values to any base temperature (below the region of body cooling by evaporation) to illustrate the effect of increased air movement. In the present case we have determined the radiation and convection constants at 60.8F and then applied the results to a base of 68F (Table 3), since the latter temperature is the approximate comfort point for clothed subjects with the initial low air movement of 9 feet per minute. To make this clear, the initial Fahrenheit value of 68° in Column B of Table 3 could be replaced by any value between approximately 60° and 75°, and the successive entries below this value determined by adding 1.6°, 3.8°, 5.2°, etc., to the new base. The latter temperature values are, of course, the successive differences between the present entries in Column B.

To solve the problem, we want to find the common air and wall temperature required at increasing velocities, assuming the radiation and convection (R + C) component of total body heat loss to be constant at 49.2 KgCal per (hr) (sq meter)—that is, 98.4% of a met or 18.14 Btu per (hr) (sq ft). Since for small differences of temperature the radiation coefficient of heat loss, cited as .68 Btu per (hr) (sq ft) (F), will behave as a constant, our only problem is to adjust the convection factor. For the condition cited,

$$K_R\,(T_{cloth} - T_R) + k_c\sqrt{V}\,(T_{cloth} - T_A) = .984 \text{ met}$$

Where K_R = radiation coefficient
T_{cloth} = surface temperature of clothing
T_R = surface temperature of walls
k_c = a convection coefficient
V = velocity of air
T_A = air temperature
met = a standard value for human heat production, clothed and sitting at ease; defined as 50 KgCal per (hr) (sq meter) or 18.43 Btu per (hr) (sq ft).

In cgs units of the original work,

$$3.32\,(25 - 16) + (1)\,(\sqrt{4.6})\,(25 - 16) = 49.2 \text{ KgCal per (hr) (sq meter)}$$

In English units, with air velocity expressed in feet per second and other variables as noted,

$$.68\,(77 - 60.8) + (1.14)\,(\sqrt{.15})\,(77 - 60.8) = 18.14 \text{ Btu per (hr) (sq ft)}$$

If one replaces the temperature differentials by X, adjusts the term under the radical for increasing air velocities and keeps (R + C) constant, successive solutions yield the required degree differences between clothing and environment required to give constant heat loss with increasing air movement, and in Table 3 these results have been expressed in degrees F as well as in the original units of the report.

TABLE 3—VARIOUS ENVIRONMENTS FOR CONSTANT HEAT LOSS

Air Velocity			Col. A Deg. F temp differ. to transfer .984 Met	Col. B Comparable air temps for noted air velocities	
Miles per hr	Cm per Sec	Approx. Fpm		Deg C	Deg F
0.1	4.6	9	16.2	20.0	68.0
0.17	7.5	15	14.6	20.9	69.6
0.34	15.0	30	12.4	22.1	71.8
0.50	22.5	45	11.0	22.9	73.2
0.67	30.0	60	10.1	23.4	74.1
0.84	37.5	75	9.4	23.8	74.8
1.00	45.0	88	8.8	24.1	75.4
2.00	89.4	176	7.0	25.1	77.7
3.00	134	264	5.9	25.7	78.3
4.00	179	352	5.4	26.0	78.8
5.00	224	440	4.9	26.3	79.3
6.00	268	528	4.5	26.5	79.7
7.00	313	616	4.1	26.7	80.1
8.00	358	704	4.0	26.8	80.3
9.00	402	792	3.8	26.9	80.4
10.00	447	880	3.6	27.0	80.6

It may be noted that for the usually low air movement of 15 fpm or less, typical of radiantly heated rooms, the normal heat loss is provided by a temperature less than 70F. For houses heated by forced warm air with air movements of the order of 30 and sometimes 40 fpm, the comparable heat loss point is 72 to 73F.

The values should not be interpreted as a criticism of either style of heating, and it is by no means demonstrated that panel systems always have air movements below 15 fpm and forced air systems velocities near 30 fpm. However, for individuals who are interested in factors which, under certain circumstances, can produce significant differences in the air temperature comfort point, this is a factor to be considered. With the present availability of low range anemometers in the equipment of the ventilating specialists, the measurement of such factors as air movement is no longer an unreliable procedure.

Effect of Humidity on Nose and Throat

With the recent publication of data indicating that the survival time of respiratory tract organisms is least at moderate relative humidities (near air temperatures of 70F) more attention is being given to the problem of humidification. With many individuals, drying of skin and mucous membrane is an important source of winter discomfort. Few studies have been made of this factor. It will be sufficient here to quote an excerpt (9) from a report by a member of the Pierce Foundation staff.

"Quite independent of the influences of atmospheric humidity upon thermal interchanges discussed previously, is the direct influence of a dry atmosphere upon the mucous membranes of the nose and throat. Huntington (7) has presented convincing evidence that dry climates and seasons are associated with definite increases in mortality rates; but the nature of the influence exerted has been little understood. Many physiologists have shown that, in general, the expired air approaches body temperature and 100% relative humidity. Therefore, it is clear that the moisture taken from the membranes of nose and throat in respiration must vary with the temperature and humidity of the inspired air. The most exhaustive study of this subject was presented to the Society by Seeley (8) in 1940. Seeley found that (except in very cold atmospheres) the expired air had a temperature of 90 to 95F and was over 90% saturated with moisture, containing 30 to 37 grams of water per cubic meter of respired air. Since this value is approximately constant, it is clear that the drying effect on the mucous membrane must be related to the absolute—not the relative—humidity of the atmosphere."

Recent studies at the John B. Pierce Laboratory of Hygiene (9) have directly confirmed this conclusion. In these experiments, direct observations were made of the moisture actually present on the surface of the back of the throat (as measured by the amount of moisture absorbed by blotting paper from a given surface under standard conditions). The relation of the phenomenon to absolute humidity was confirmed; and an interesting critical point in the process determined.

At atmospheric water vapor pressure below 0.4 inch of mercury at any temperature (from 50F to 80F), the throat surface was very definitely dry. Between 0.4 and 0.5 inch, a very marked increase in moisture was manifest, equal to a sudden doubling of the water absorbed by the blotting paper. At a still higher vapor pressure a secondary decrease in moisture on the mucous surface was observed at certain points (70F with 70% R.H., and 80 F with 50% R.H.) which is believed to be associated with vasomotor reactions related to the onset of sweat secretion. The point of primary interest, however, is the critical point at 0.4 inch vapor pressure. This finding means that marked drying of the membranes of the nose and throat must occur at air temperatures below 53F with any moisture content up to saturation; at a dry-bulb temperature of 60F with less than 77% R.H.; at a dry-bulb temperature of 70F with less than 54% R.H.; and at a dry-bulb temperature of 80F with less than 39% R.H.

It should be emphasized that there is no direct evidence that the drying of the mucous surfaces is actually undesirable. The general opinion that very dry air irritates the throat and the clinical practice of treating the membranes of persons suffering from bronchial disease by soothing inhalations would seem to suggest that the problem may be of importance. If dry air is harmful, it seems obvious that its influence must be present, not merely in hot, dry air, as has often been thought, but quite as much in cold, dry air. Furthermore, it appears that if it is desired to control the influence of dry air on the mucous membranes, a relatively high vapor pressure must be maintained corresponding at 70F to over 50% R.H.

In Fig. 2, a graph is shown of throat moisture in relation to vapor pressure.

In view of the potential importance of a relative humidity of approximately 50% (near 70F) in relation to bacterial survival, the comfort significance of humidification must receive further consideration.

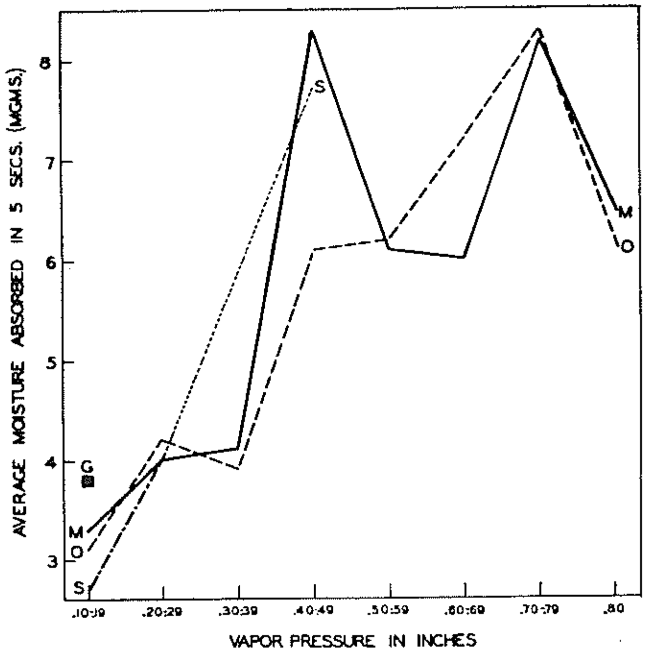

Fig. 2. Average moisture absorbed from the throat after 3 hours of exposure to each vapor pressure for each temperature.

Regional Heating of the Human Body

Radiant panel systems introduce heat usually from either floor or ceiling. In ceiling systems it has been customary to keep design conditions such that the space is adequately heated without exceeding panel surface temperatures by 100F in rooms with 8-foot ceilings. Temperatures beyond this are associated with unpleasant degrees of heat sensation on the head and face.

In floor panel systems a similar problem is met in restricting surface temperatures to values which do not result in overheating of the feet. The utility of floor systems and their comfort possibilities in basementless homes constructed on concrete slabs is such that proponents of such systems should give attention to the problem of permissible floor temperature limits.

During a recent spring day of ideal indoor comfort, the following temperature relations were recorded at the Pierce Laboratory (subject had been seated quietly for several hours):

	F
Outdoor Air Temperature	68.5
Mean Wall Temperature	72.0
Ceiling Temperature	73.5
Floor Temperature	71.1
Air Temp. 30″ level	70.6
Air Temp. 66″ level	72.5
Air Temp. 120″ level	73.3
Outside Shoe Surface	73.9
Ventral Skin of Foot	87.7
Lower Surface of Toes	84.6
Skin Surface of Calf	91.1
Skin Surface of Thigh	92.5
Skin of Hands and Fingers	93.1
Trunk Surface	95.0
Cheek	95.8

It is obvious from the foregoing data that outside shoe temperatures are 10 degrees or more below foot surface temperature. It is also clear that with floor temperatures of the order of 80F the skin surface temperature of the foot must rise considerably above the range of 78F to 85F that has been observed for a group of individuals with comfortable conditions and floor temperatures of the order of 70F.

In this laboratory the general physiological criteria of thermal comfort have been described in many experimental studies. Data drawn from the representative article cited here, and from the survey article on skin temperature and human heat regulation by Sheard (10) make it quite apparent that one of the primary conditions of thermal comfort is a skin temperature ranging from approximately 80F on the toes and sole of the foot to approximately 95F on the trunk and certain facial areas, with an over-all average for the skin surface of 90F to 92F.

The low temperatures on the feet are the net result of (1) a large surface-small volume factor, and (2) the practical circulatory necessity of high vascular tone in the lower extremities as an anti-gravity adjustment favoring competent circulation in the more vital body regions. One of the conditions of an alert subjective state is the maintenance of this vascular tone, and in consequence, foot temperatures are very considerably below the general skin average.

This problem has recently been summarized in an experimental report (11). The author is definitely of the opinion that arrangements of floor heating systems in such a manner as to provide highest temperatures near the periphery, with most frequently occupied central floor areas restricted to values of approximately 75F, is desirable. A fuller discussion of this point may be had in the reference given.

Human Efficiency and Thermal Environment

The efficient performance of the human body and a personal sense of well being is definitely related to the temperature environment in which we exist. In the closing section of this article I should like to relate two items to this general problem which have not received the attention they deserve. One of these items is the relation of temperature and posture, the other the effect of unfavorable thermal environments on the accuracy of human performance.

To gain an over-all subjective sense of the personal factors which are subtly affected when thermal conditions are not ideal, let us look at the extremes of human postural reaction to thermal stress. Imagine a nude subject placed in a cooled chamber at sub-zero temperatures. After a sufficient length of time, he will be found in rigid posture, arms and legs folded against the body and fixed in a general pattern of contracted muscular rigidity. Although this posture may have been preceded by stimulation with violent exercise and bouts of shivering, observation would confirm the fact that from the very beginning the subject has reacted to the cold with a basic pattern in which sharp increase in muscle tension is the most conspicuous factor. In due time voluntary inhibition of this pattern of muscle contraction becomes impossible and the individual is locked in a tightly contracted posture so severe that even the respiratory muscles are affected and breathing becomes extremely difficult. This rigidity is not due in any sense to being frozen stiff. If the exposure persists, at death his musculature will temporarily relax. Such a subject in reality is exhibiting the ultimate degree of a deep-seated actively organized and involuntary reflex to cold which is a basic part of temperature regulation. Such contracted postures reduce the surface area for heat loss, and in earlier stages provide a strong stimulus for both exercise and involuntary shivering, as means of increasing heat production.

Contrast this picture with that of the man exposed to a temperature of 140F to 150F. We see no initial period of active stimulation, no sharply defined postures indicating high muscle tone. Instead of standing or running, the subject droops in a listless fashion. Posture, in the ordinary sense of the word, decays, and upright stance requires voluntary effort. In due time, after exhaustive sweating and body dehydration, the subject sinks to the floor. Here he lies in a relaxed spread-eagle attitude, muscles limp and his body exposing maximum surface to the environment. In contrast to the labored respiration and slow pulse of the cold exposure, the heat victim has a rapid shallow respiration and elevated pulse rate. Aside from such physiological details, we are principally impressed by the picture presented of extreme muscular relaxation and the absence of a positive organized posture.

Such extremes of heat or cold exposures are seldom either seen or experienced by the average person. In both cases we note that temperature regulation has been unequal to stress and that immobility, and perhaps death, follow the deviation of the deep body temperature from its tolerable range in either direction. The intimate physiology of the respiratory, circulatory, and body fluid chemical changes that occur at either extreme, are beyond our interests here. However, the dramatic and sharply contrasting postural and muscular effects of the two extreme thermal situations may be readily appreciated, and the probable subjective character of the two different types of stress easily imagined.

What is important for the appreciation of the nature of ordinary ranges of thermal discomfort is the fact that the above illustrations dramatize the extremes of a continuous body function, namely, dynamic maintenance of posture and the alternating postures which comprise physical activity in relation to temperature and the conditions of body heat production and loss. Our subjective sense of the activity and adequacy of the postural functions is difficult to describe, but it is certain that this subjective element is one of the highly important components of our personal sense of comfort and well-being. There are many reservations and qualifications necessary for a full scientific description of the effect of thermal influences on efficiency and subjective comfort. Basically, however, we may say with assurance that the progressive decay of posture in warm environments, and its accentuation, breaking over into a desire for physical action in cool environments, are extreme examples of a marked reflex association between temperature and posture regulation mechanisms. At the extremes of exposure we are not able, by voluntary effort, to support a posture contrary to the pattern set by this association. We are completely immobile, rigid, or relaxed according to the thermal circumstances. In the usual range of environmental temperatures we may choose to work quietly despite a vague but persistent urge for movement, or we may work resolutely at a task despite a recurrent desire to relax and take it easy. Postural accentuation or inhibition incongruent with the activity at hand may, no doubt, arise from many sources, some of them of a social or psychological nature. One scientific end of physiologically acceptable air conditioning is, however, the production of thermal environments in which the involuntary component of posture maintenance is consonant with the requirements of particular types of work, rather than contrary to these requirements. Even though the deviation from an ideal atmosphere is slight, if the tasks at hand, or the pursuit of the interests and activities desired, do not permit an adjustment of activity or posture consonant with the subtle change of postural tone which is thermally determined, the individual experiences distraction and a subjective sense of effort which is unpleasant and fatiguing.

Our use of the term "posture" in these illustrations has been broad, in the lay sense of the term. Such use is, however, physiologically sound, and includes not only static postures, but the succession of postures which constitute organized movement. Such use also implies that the static posture is in reality a highly organized dynamic process representing not inaction but a well-integrated physiological activity. The reflex associations determining these postural reactions to temperature are primitive and deeply rooted in the nervous system of all warm-blooded organisms. Within moderate temperature ranges man, by consciously determined effort, may standardize his posture and activity, counter to persistent natural tendencies determined by his immediate thermal situation. No doubt the perennial interest in the weather as a topic of conversation, and the persistence with which the elusive concept of the ideal atmosphere has been investigated, both reflect a rational interest in an important problem, but also unconscious human acknowledgment of the fact that temperature regulation holds a top priority among involuntary neural functions, and one not always respected in our choice of working and living environments.

From these remarks it must be evident that the conditions determining heat exchange with man's environment are not only of great interest to biology, but that an understanding of this problem is fundamental to the scientific provision of atmospheric conditions conducive to health and comfort.

In conclusion I want to cite the second neglected item mentioned above, and to present briefly data on the relation of climatic optima to working efficiency. I choose the category of accidents and errors. No one wants an accident or error consciously, and their occurrence is an index of uncertainties and confusion in human action. In a sense these data are a confirmation in an objective field of the remarks made on the close relation between temperature and posture control. In many instances an accident is actually the result of unplanned posture. Your hand, shall we say, miscued in the wrong place at the wrong time, or your eyes got out of gear with local space reality; these are examples of such postural accidents. I shall give three illustrations relating to accidents in three types of human work: Heavy manual labor, light, semi-skilled factory work, and a highly skilled activity with a large mental component. In reference to manual labor, it has been convincingly demonstrated that in a heavy task such as coal mining, accident rates are lowest in mines where temperatures average near the 60F level, which is optimum for the level of body heat production involved in this work.

In light factory assembly work, heat production is much lower and the physiologically desirable temperature optimum moves higher to a point near 67F. In an extensive observation made on this type of work, accidents were found to increase both *above* and *below* a temperature of 67F. This is interesting in that it indicates that the environment which is too cold leads to postural awkwardness that is as accident provocative as the warm environment which promotes lassitude and mental dullness.

In a final category we have convincing information on the effect of heat on the complex mental task of wireless code reception. Here errors in reception may be considered to be accidents. Careful studies of this activity have shown conclusively that the incidence of mental awkwardness, as evidenced by incorrect reception, increases with temperature stress.

From these evidences of the serious decay of human accuracy and dependability under climatic conditions which are not optimal for a given kind of work, we may draw this conclusion. If we were in a position to grade and evaluate all human activity as positively as we can measure average accident and error experience, we would probably be astonished at the price in wasted energy that our society, our business organizations, and our families pay for work under unfavorable and poorly controlled atmospheric conditions.

I think it is reasonable to say that the full use of our technical resources for indoor climatic control is very much dependent upon wider recognition and understanding of the human effects here discussed.

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